From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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The new record holder for the most iron-poor star: HE 1327−2326, a dwarf or subgiant with [Fe/H] $= -5.4$

A. Frebel[1]
W. Aoki[2], **N. Christlieb**[3], **H. Ando**[2], **M. Asplund**[1], **P. S. Barklem**[4], **T. C. Beers**[5], **K. Eriksson**[4], **C. Fechner**[3], **M. Y. Fujimoto**[6], **S. Honda**[2], **T. Kajino**[2], **T. Minezaki**[7], **K. Nomoto**[8], **J. E. Norris**[1], **S. G. Ryan**[9], **M. Takada-Hidai**[10], **S. Tsangarides**[9] and **Y. Yoshii**[7]

[1]Research School of Astronomy & Astrophysics, Australian National University, Australia
email: anna@mso.anu.edu.au

[2] National Astronomical Observatory of Japan, Japan

[3] Hamburger Sternwarte, Germany

[4] Department of Physics & Space Sciences, Uppsala Astronomical Observatory, Sweden

[5] Department of Physics & Astronomy, and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, USA

[6] Department of Physics, Hokkaido University, Japan

[7] Institute of Astronomy, School of Science, University of Tokyo, Japan

[8] Department of Astronomy, School of Science, University of Tokyo, Japan

[9] Department of Physics and Astronomy, Open University, UK

[10] Liberal Arts Education Center, Tokai University, Japan

Abstract. We describe the discovery of HE 1327−2326, a dwarf or subgiant with [Fe/H] $= -5.4$. The star was found in a sample of bright metal-poor stars selected from the Hamburg/ESO survey. Its abundance pattern is characterized by very high C and N abundances. The detection of Sr which is overabundant by a factor of 10 as compared to iron and the Sun, suggests that neutron-capture elements had already been produced in the very early Galaxy. A puzzling Li depletion is observed in this unevolved star which contradicts the value of the primordial Li derived from WMAP and other Li studies. Possible scenarios for the origin of the abundance pattern (Pop. II or Pop. III) are presented as well as an outlook on future observations.

Keywords. stars: individual (HE 1327−2326), stars: abundances

1. Introduction

Observations of metal-poor stars with [Fe/H] < -3.0 provide crucial clues to the formation of the first objects in the Universe and their contribution to its chemical enrichment. The detailed abundance analyses of such stars reveal observational details which are compared to theoretical models for nucleosynthesis yields originating from e.g. first generation supernovae, in order to learn about the chemical evolution of the Galaxy.

Until recently only one star was known to have an iron abundance with [Fe/H] < -4.0 (HE 0107−5240 with [Fe/H] $= -5.2$; Christlieb et al. 2002). Now, a second star, HE 1327−2326, has been found with [Fe/H] $= -5.4$ (Frebel et al. 2005, Aoki et al. in preparation). These objects provide insight into the early Universe because the existence of the two low-mass stars challenges the current scenarios for the formation of the very first stars after the Big Bang. The abundance patterns of both stars pose many questions

to observers and theoreticians and much progress has been made in order to explain how these very particular objects could form. This paper describes the very recent discovery of the new record holder for the most iron-poor object, HE 1327−2326.

2. Bright metal-poor stars from the Hamburg/ESO Survey

Thus far, the Hamburg/ESO (HES) survey was only investigated for its fainter metal-poor stars (Christlieb et al. 2003, Beers et al., this volume). However, it was recently extended to the brighter end ($10 < B < 14$; Frebel et al. in preparation). Despite partial saturation effects, it was possible to select a sample of 1777 bright metal-poor candidate stars.

Three observational steps are necessary to identify the most metal-poor stars. Figure 1 illustrates these steps. Medium-resolution follow-up spectroscopy ($\sim 2\,\text{Å}$) of the entire sample of bright stars was recently completed. In April 2003, a medium-resolution spectrum of HE 1327−2326 was taken with the ESO 3.6 m telescope. Using the Ca II K line at 3933 Å and the Beers et al. (1999) calibration we derived an iron abundance of [Fe/H] $= -4.3$. High-resolution spectra of HE 1327−2326 with the Japanese Subaru telescope and its High Dispersion Spectrograph were taken in May and June 2004 (see Aoki et al., this volume). It was immediately revealed that the metallicity estimate obtained from the medium-resolution data was greatly overestimated due to the presence of interstellar Ca II. The interstellar feature was not resolved at lower resolution, thus blending with the stellar Ca II K line. Reddening of $E(B-V) = 0.08$ (Schlegel et al. 1998) in the line-of-sight is consistent with the presence of the interstellar Ca II (see bottom panel of Figure 1).

Further high-resolution spectroscopy of the most metal-poor stars from the bright sample is currently underway.

3. Stellar parameters of HE 1327−2326

From $BVRIK$ photometry obtained with the 2 m Magnum telescope (University of Tokyo) we derive an effective temperature of $T_{\rm eff} = 6180 \pm 80\,\text{K}$, based on the Alonso et al. (1996) scale. This temperature is consistent with the values derived from a Balmer line profile analysis.

Due to the absence of Fe II lines in the spectrum of HE 1327−2326, the gravity could not be determined in a spectroscopic fashion. Both neutral and ionized species are needed to derive the gravity from the ionization equilibrium. One Ca I and two Ca II lines are detected in HE 1327−2326. Hence, Ca could in principle be used instead of iron. Using 1D MARCS and Kurucz model atmospheres, the large difference of 0.8 dex between the Ca LTE abundances derived from Ca I and Ca II lines suggests that significant NLTE effects are present. Thus, we refrained from using Ca for the gravity determination. Instead, from the known proper motion of HE 1327−2326 we inferred an upper limit on its distance and hence its absolute visual magnitude. This information leads to two different solutions for the gravity when an isochrone for [Fe/H] $= -3.5$ (Kim et al. 2002) is employed. It follows that HE 1327−2326 is a dwarf ($\log g = 4.5$) or a subgiant ($\log g = 3.7$). There is no significant difference in the abundances derived for both cases. The astrophysical implications are not effected by this uncertainty.

Regarding the iron abundance, we applied a $+0.2$ dex NLTE correction (Asplund 2005) resulting in [Fe/H] $= -5.4$ for HE 1327−2326.

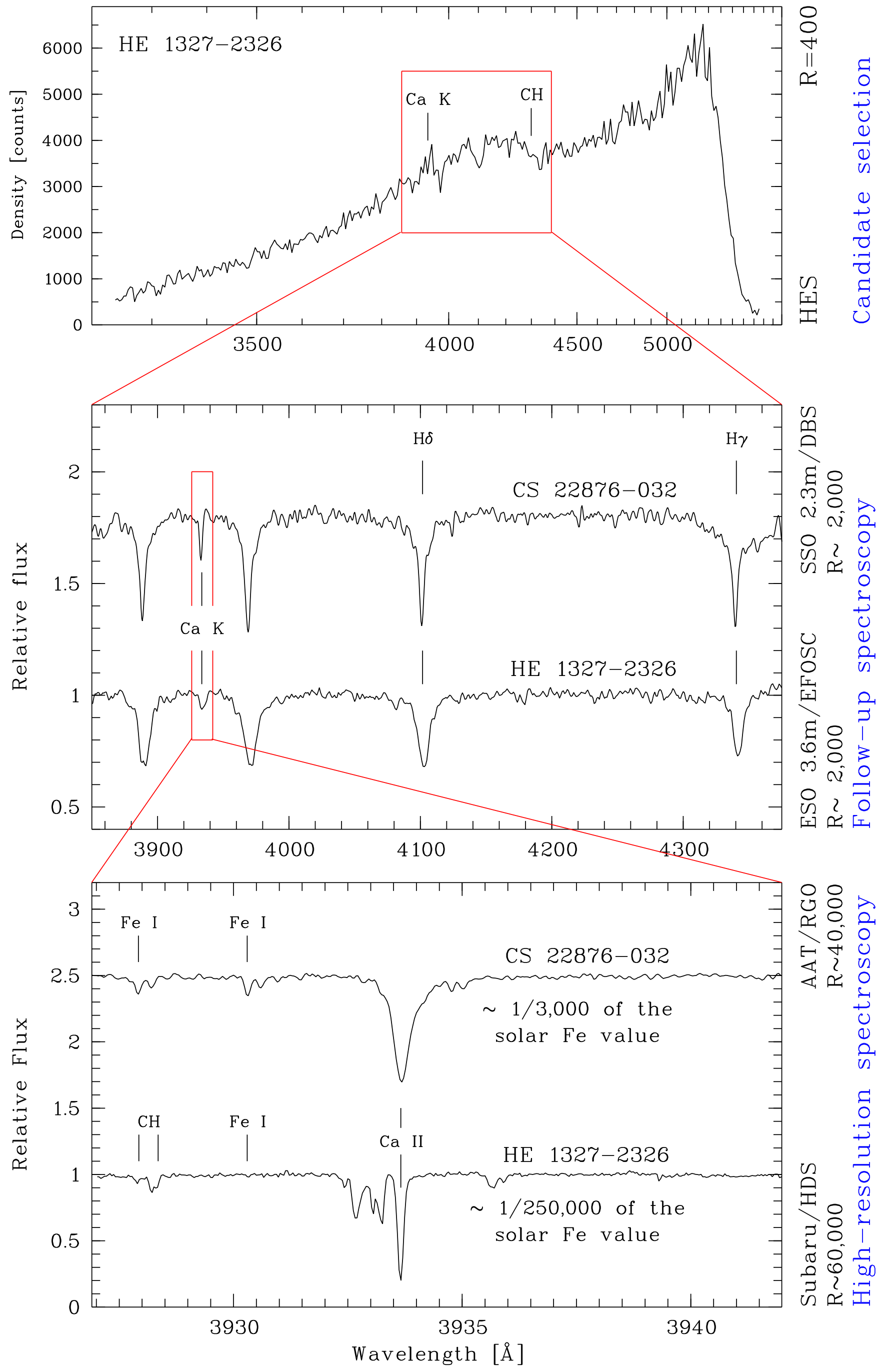

Figure 1. The three observational steps to find metal-poor stars illustrated by means of HE 1327−2326. Top panel: HES objective-prism spectrum. Middle panel: Medium-resolution spectrum of HE 1327−2326 in comparison with CS 22876−032 ([Fe/H] = −3.7; Norris et al. 2000 and references therein). From this data we measured [Fe/H] = −4.3 for HE 1327−2326 because interstellar Ca blended with the Ca II K line. Bottom panel: High-resolution spectra of both objects. Only with the high-resolution data was it possible to determine the true iron abundance, [Fe/H] = −5.4, for HE 1327−2326.

Table 1. Abundance pattern of HE 1327−2326 as reported in Frebel et al. 2005

Element	[Element/Fe], A(Li), [Fe/H] Subgiant	Dwarf
Li	< 1.6	< 1.6
C	4.1 ± 0.2	3.9 ± 0.2
N	4.5 ± 0.2	4.2 ± 0.2
O	< 4.0	< 3.7
Na (LTE)	2.4 ± 0.2	2.4 ± 0.2
Na (non-LTE)	2.0 ± 0.2	2.0 ± 0.2
Mg (LTE)	1.7 ± 0.2	1.7 ± 0.2
Mg (non-LTE)	1.6 ± 0.2	1.6 ± 0.2
Al (LTE)	1.3 ± 0.2	1.3 ± 0.2
Al (non-LTE)	1.7 ± 0.2	1.7 ± 0.2
Ca I	0.1 ± 0.2	0.1 ± 0.2
Ca II	0.9 ± 0.2	0.8 ± 0.2
Ti	0.6 ± 0.2	0.8 ± 0.2
Fe (LTE)	-5.6 ± 0.2	-5.7 ± 0.2
Fe (non-LTE)	-5.4 ± 0.2	-5.5 ± 0.2
Sr (LTE)	1.0 ± 0.2	1.2 ± 0.2
Sr (non-LTE)	1.1 ± 0.2	1.3 ± 0.2
Ba (LTE)	< 1.4	< 1.7
Ba (non-LTE)	< 1.4	< 1.7

Table 2. Radial velocity measurements of HE 1327−2326 from high-resolution data obtained with Subaru/HDS

	UT date	v_{rad} [km/s]
2004	May 30	63.9
2004	June 02	64.0
2004	June 27	63.6
2005	February 27	63.8

4. Summary of the Abundances and Radial Velocity Measurements

HE 1327−2326 has an exceptionally low iron abundance of [Fe/H] $= -5.4$ in combination with extremely high [C/Fe] and [N/Fe] (~ 4 dex overabundance). See Table 1 for the abundances derived for the dwarf and the subgiant case. [Mg, Na, Al/Fe] are enhanced by more than one dex while [Ca, Ti/Fe] are only slightly overabundant. Surprisingly, the only detected neutron-capture element, Sr, is enhanced by a factor of 10 as compared to iron and the Sun. Li is depleted in this unevolved star and only an upper limit of $\log \epsilon(Li) = 1.6$ could be inferred. This significantly contradicts the results from other Li studies using unevolved metal-poor stars (Ryan et al. 1999) as well as the recent WMAP results which is much higher (by ~ 1 dex; Coc et al. 2004). There is no obvious reason why the Li is depleted. Possible ideas are that HE 1327−2326 might perhaps be a fast rotator or a member of a binary system. However, no significant line broadening was found amongst the 17 weak absorption lines used for the abundance analysis.

In order to test the binary scenario radial velocities have been determined from high-resolution observation for four different epochs. All values agree within their measurement errors which are ~ 1 km/s. The results are summarized in Table 2. The apparently constant radial velocity has a variety of implications for the origin of the abundance pattern of HE 1327−2326 because it indicates no membership of a binary system. However, it might still be possible that the star is a long-period, low-amplitude binary. This has been

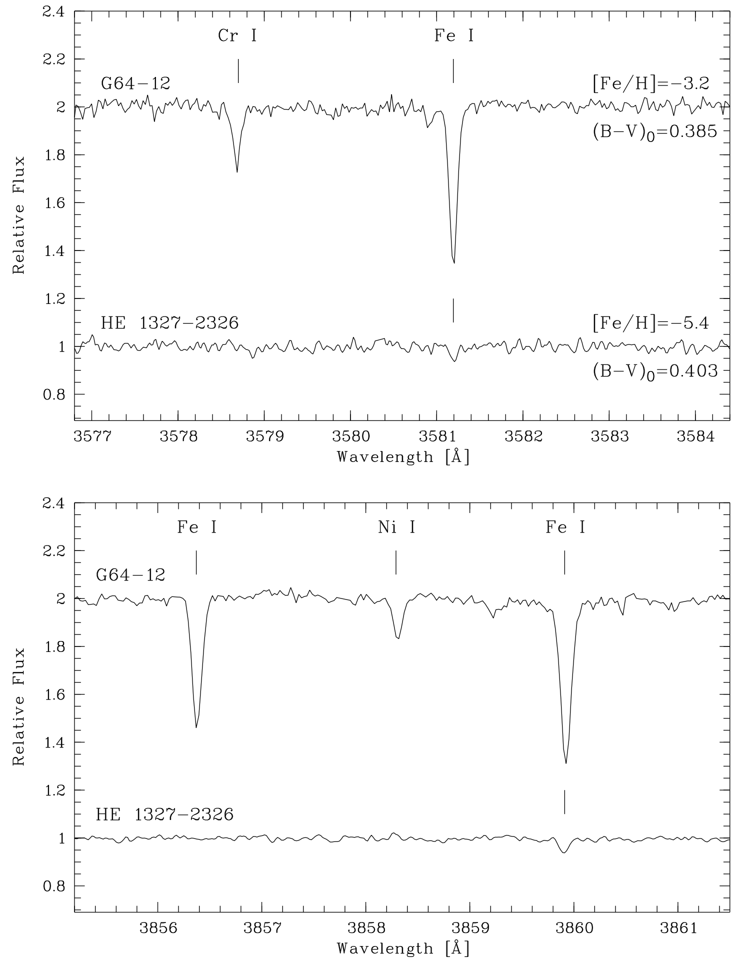

Figure 2. The two stronger Fe I lines detected in the spectrum of HE 1327−2326. The lines at 3581 Å has 5.9 mÅ equivalent width, while the line at 3859 Å has 6.8 mÅ. In total, we detect four Fe I lines. The other two have equivalent width of 2.5 mÅ and 1.9 mÅ respectively.

previously suggested to be the case for HE 0107−5240 (Christlieb et al. 2004b; Suda et al. 2004). A binary scenario for HE 1327−2326 would be able to explain the Li deficiency. To clarify the situation, radial velocity monitoring of HE 1327−2326 and HE 0107−5240 is underway.

The observed Sr/Ba ratio of [Sr/Ba] > -0.4 in HE 1327−2326 is inconsistent with that found in s-process-rich stars which have [Sr/Ba] < -1.0. Hence, mass transfer of s-process elements from a possible former companion seems to be ruled out. The upper limit of the Sr/Ba ratio is, however, consistent with the ratio found in strongly r-process enhanced stars (e.g. Christlieb et al. 2004a). This is supportive of an abundance pattern originating from pre-enrichment by previous generation supernovae under the assumption that the main site of the r-process is in supernovae.

5. Possible Origins of the Abundance Pattern

There are currently two main different scenarios with which the abundance pattern of HE 1327−2326 might be explained. First, there is a Population II scenario which invokes

pre-enrichment by a previous generation star by means of a stellar wind or a supernova explosion (Iwamoto et al. 2005; Nomoto et al., this volume; Meynet et al. 2005, Meynet et al., this volume). Another possibility is that HE 1327−2326 is a population III star, which accreted the heavier elements observed on its surface from the interstellar medium. Lighter elements, such as CNO, would have been donated from a former AGB companion through mass transfer. The assumption that the star would be long-period, low amplitude binary is a crucial ingredient.

6. Conclusions and Outlook

Further work is required to determine the origin of the abundance patterns of HE 1327−2326 and HE 0107−5240. One crucial model-ingredient will be the oxygen abundance of HE 1327−2326. In particular it will challenge the Population II scenario of Iwamoto et al. and simultaneously provide a test on the AGB scenario. Hence, 21 h of VLT/UVES time have recently been granted to attempt the detection of OH features in the UV.

Clearly, more objects are needed to enlarge the sample of extremely iron-deficient stars in order to study the phenomena occurring at that low metallicity range. Using the HES, efforts are underway to observe further metal-poor candidates as well as to process additional 51 HES plates to produce even more candidates which might eventually lead to the discovery of more stars with [Fe/H] < -5.0.

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